CHAMP:
Camera, Hand lens, And Microscope Probe

John Boynton, Greg Mungas, Cesar Sepulveda, Mark Balzer, Luther Beegle, Harold Sobel
Jet Propulsion Laboratory
4800 Oak Dr. Pasadena CA 91108-8099
Email: {Greg.S.Mungas, John.E.Boynton, Cesar.A.Sepulveda, Mark.A.Balzer, Luther.Beegle, Harold.R.Sobel}@jpl.nasa.gov
Ph: 818-393-6719

Ted Fisher
Firestar Engineering, LLC
557 Unit J, Louisville, CO 80020
Email: Ted.Fisher@firestar-engineering.com
Ph: 303-439-2698

Dan Klein
Coherent Technologies
Email: dan_5422@yahoo.com

Matthew Deans, QSS Inc.
NASA Ames Research Center
MS 269-3 Moffett Field, CA 94035
Email: mdeans@arc.nasa.gov

Pascal Lee
NASA Ames Research Center
MS 245-3 Moffett Field, CA 94035
Email: pclee@marsinstitute.info
Ph: 408-687-7103

Abstract—CHAMP (Camera, Hand lens And Microscope Probe)[1,2] is a novel field microscope capable of color imaging with continuously variable spatial resolution from infinity imaging down to diffraction-limited microscopy (~3 μm/pixel). As a robotic arm-mounted imager, CHAMP supports stereo-imaging with variable baselines, can continuously image targets at an increasing magnification during an arm approach, can provide precision range-finding estimates to targets, and can accommodate microscopic imaging of rough surfaces through a image filtering process called z-stacking. CHAMP was originally developed through the Mars Instrument Development Program (MIDP) in support of robotic field investigations, but may also find application in new areas such as robotic in-orbit servicing and maintenance operations associated with spacecraft and human operations. We overview CHAMP's instrument performance and basic design considerations below.

TABLE OF CONTENTS

1. INTRODUCTION

Imaging over a wide range of spatial scales constitutes a fundamental aspect of many facets of aerospace exploration including robotics (e.g. reconnaissance, navigation, and instrument and tool placement), planetary sciences (e.g. geology, astrobiology) and engineering sciences (e.g. surface metrology).

To provide a brief example of "lessons learned" for in-situ imaging, the recent Mars Exploration Rover (MER) mission is considered. Over the mission, the mast-mounted Panoramic Imager (Pancam) has been developed and utilized extensively to perform remote geologic investigations of surrounding terrain, provide context imaging for remote-sensing and contact instruments, assess rover hazards, and guide rover navigation and arm placement. The Microscopic Imager (MI), an arm-mounted hand-lens for the MER investigation, has been an essential instrument for investigations into the microscale realm of Mars. Specifically, tabular vugs, spheroidal concretions, and finely-layered rippled bedforms have been imaged with the MI to support the conclusion that a shallow aqueous and salt-rich environment existed when sediments were deposited at the Meridiani landing site. Despite this utility, at the Gusev Crater landing site, it was inferred that a substantial fraction of particles were too small to be resolved with the MI. Furthermore, the utilization of ambient lighting conditions restricted MI operations to optimum lighting conditions. Finally, the MI's lack-of-color (monochromatic) imaging put a constraint on data interpretation [1-6].

Current spaceflight imagers have rather limited focus/magnification ranges with imaging performance as follows:

[1] 0-7803-8870-4/05/$20.00© 2005 IEEE
[2] IEEEAC paper #1510, Version 5, Updated December 27, 2004

1) Pancam – 0.27 mrad/pixel. 8 color filters per imager. 2 imagers for stereo-imaging with fixed baseline. No active illumination. Mass ~1kg. [6]

2) MER MI - Spatial resolution of 30 μm/pixel. No active illumination. Mass of ~0.450kg [7].

3) Robotic Arm Camera (RAC) for the 2007 Phoenix Mars Scout lander robotic arm – Spatial resolution of 23 μm/pixel. Active illumination [8, 9].

4) Fixed focus MECA microscope on the Mars 2001 lander (Phoenix 2007). Spatial resolution of 4 μm/pixel. Multiple LED illumination [9].

5) Beagle 2 microscope – Spatial resolution of 4 μm/pixel. Multiple LED illumination [10].

2. CHAMP OVERVIEW

CHAMP (Camera, Handlens, And Microscope Probe) is a new high-spatial-resolution, multi-band field camera/microscope with variable working-distance/magnification. CHAMP is capable of imaging across a wide range of spatial scales from km's to m's for context imaging (Pancam analog) down to 3 μm/pixel at peak magnification for microscopy (higher spatial resolution analog to micro-imagers 2-5 identified above). CHAMP can acquire in-focus images from almost any working distance relative to a target (~7 mm out to infinity). The resultant image resolution is directly correlated with the working distance - the closer the instrument is placed to the target, the higher the resolution/magnification of the captured image at the cost of a smaller field-of-view (FOV).

The same adjustable working distance can be utilized over small ranges to perform microscopy and imaging of unimproved "rough" surfaces consistent with field investigations through a process called z-stacking.

A filter wheel provides multi-band imaging capability (RGB with the option for additional filters for specific bandpass imaging or calibration functions). LED illumination is incorporated to provide active illumination particularly for microscopy.

Originally developed under the Mars Instrument Development Program (MIDP) in 1998-2000 and fully integrated into the NASA Ames K9 rover for IS Level I and ASTEP (Astrobiology Science and Technology for Exploring Planets) robotic field testing, CHAMP has since evolved into a space-qualifiable design as a proposed instrument for the 2009 Mars Science Laboratory (MSL) mission (total mass <1 kg). The MIDP version of this instrument with samples of acquired images is shown in Figure 1.

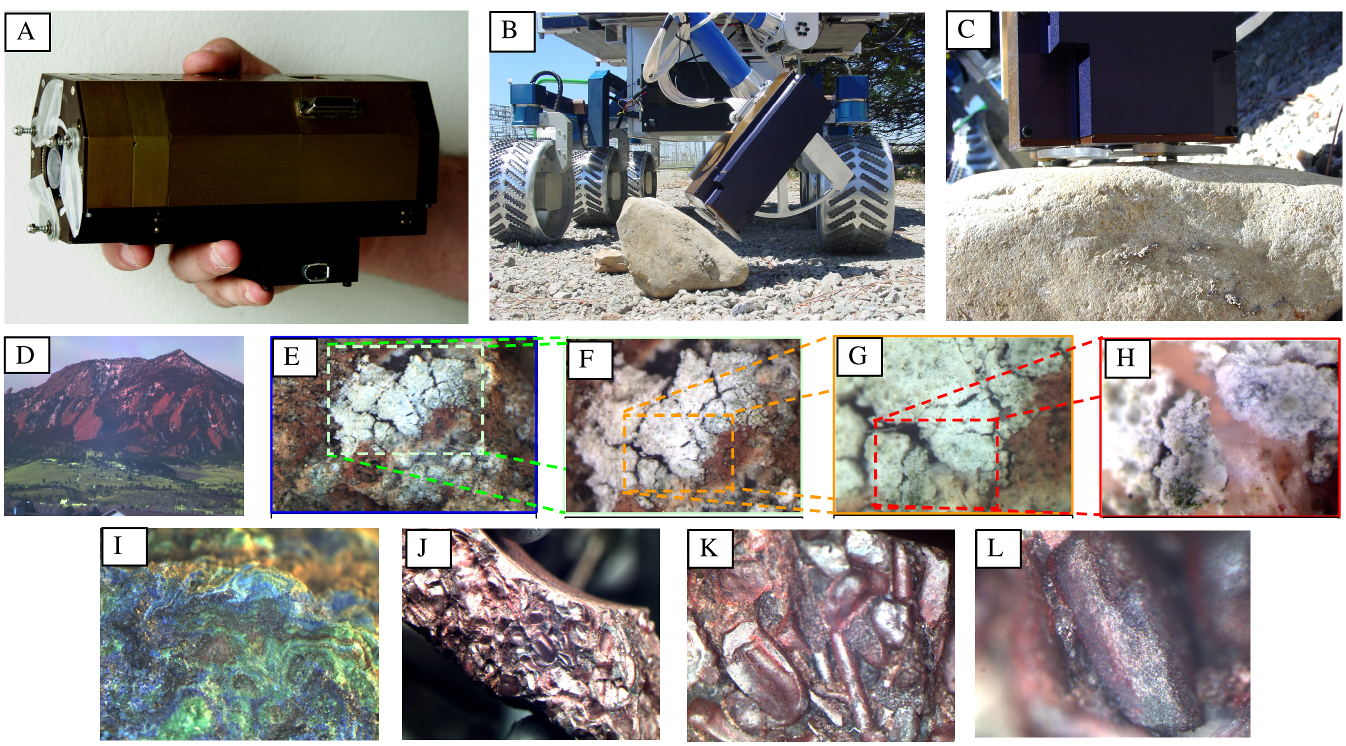

Figure 1 - A) The MIDP CHAMP Instrument B) Deployed on the NASA ARC K9 Rover, and C) Preloaded into a Target Rock for Stable Microscopic Imaging; D) Infinity Image of Rocky Mountains in Boulder, CO; E)-G) Progressive Approach to Chalcedony Target Imaged at H) Peak Magnification; I) Copper-Rich Chalcedony Rock; J) - L) Variable Magnification Images of Hematite with Micro-Fossils (No Z-Stacking, as Described Below).

3. CHAMP OPTICAL DESIGN

The CHAMP optical system consists of two lens cells which when translated relative to one another provide an adjustable working-distance/magnification. Figure 2 illustrates the CHAMP Zemax optical design with acquired images of a US$20 from the MIDP CHAMP instrument over most of the instrument's magnification range (infinity not shown due to scale). Table 1 summarizes imaging performance as a function of working-distance. At the highest magnification, (3 μm/pixel resolution), the imperfections in the micro-print from the run of the ink into the fibers of the bill are clearly visible. For comparison purposes, an image at MER's MI equivalent resolution (30 μm/pixel for a 12μm pixel) is also shown (note microprint cannot be resolved at this imaging resolution).

The CHAMP optical system has been created and optimized with 1000+ permutations of 26 simultaneous design configurations (i.e different working distances/magnifications at different operational temperatures) using Zemax optical design software [11]. The final design has been optimized for achromatic imaging from 460-650nm onto a detector with ~12 μm pixels with <1% field distortion and <5% variation in field intensity for all working-distances in the temperature range of -145°C to 50°C. FOV can be linearly scaled up from the current MIDP CHAMP design for a 512^2 array. The CHAMP optical design has been shown by Zemax Monte Carlo sensitivity analysis to be tolerant of lens alignment (i.e. tilt, decenter) and manufacturing tolerances (i.e. radii of curvature, lens thicknesses). The lenses have been designed to be mounted and precision-aligned inside two custom lens cells that can accommodate launch vibration and extreme thermal environments. Relative tolerances between these lens cells are relatively course (i.e., ~0.3° tilt).

Figure 3 illustrates the relative optical performance (Huygens modulus of optical transfer function) for various image plane field points simulated in Zemax over CHAMP's magnification range.

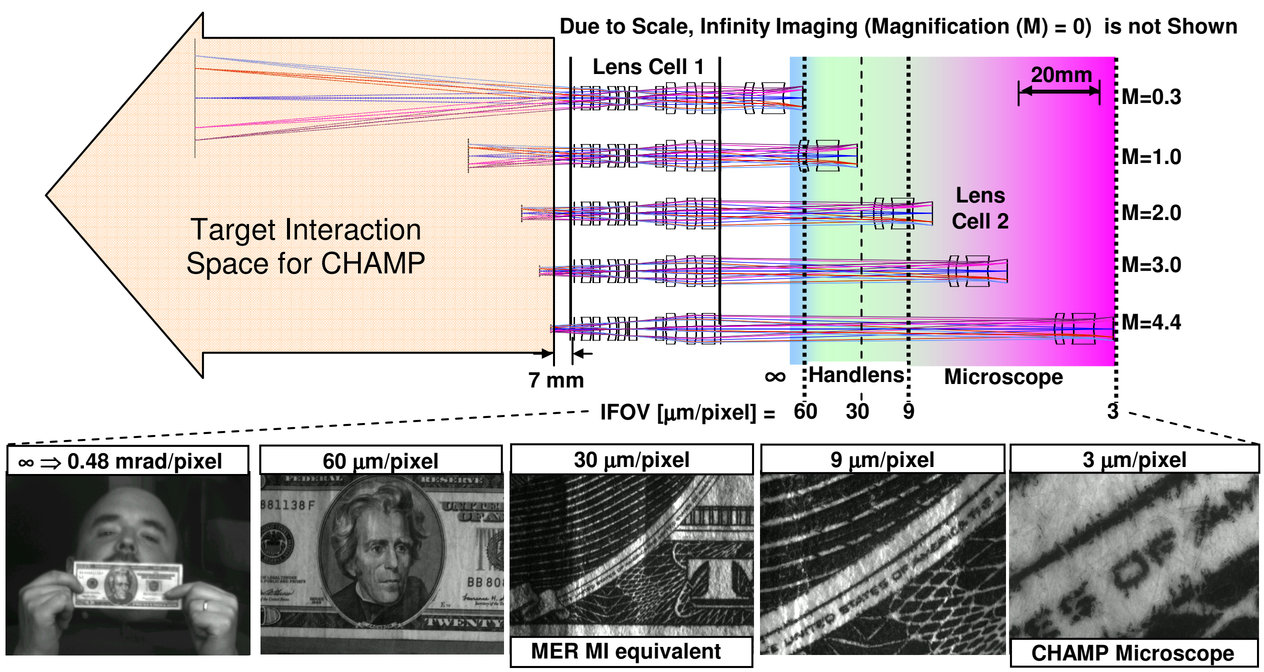

Figure 2 - CHAMP Optical Design And Monochromatic Images Acquired Over CHAMP's Magnification Range. Pixel resolution is quoted for a 12 μm pixel (optimal pixel size for design), however, a commercial 649x509 detector with 7.4 μm pixels was used to acquire images for purposes of illustrating CHAMP's relative magnification range.

Table 1. Summary of Proposed CHAMP Flight Instrument Imaging Characteristics (Larger FOV than MIDP).

	Microscopy ⟵ Working-Distance [mm] ⟶ *Infinity*								
	7	**8.4**	**10**	**14.5**	**27**	**87**	**250**	**2500**	**Infinity**
Magnification	4.4	4.0	3.0	2.0	1.0	0.3	0.1	0.01	0
Object Plane Pixel Resolution- [μm/pixel]	2.9	3.2	4.3	6.4	12	42	124	1240	0.48 mrad/pixel
Flight CHAMP Field of View (FOV) [mm]	3.0	3.3	4.4	6.6	13	43	126	1270	13.2°
Depth of field [μm]	45	49	62	95	225	1600	10^4	10^6	----
Illumination	UV or White LED				White LED		Passive Lighting		

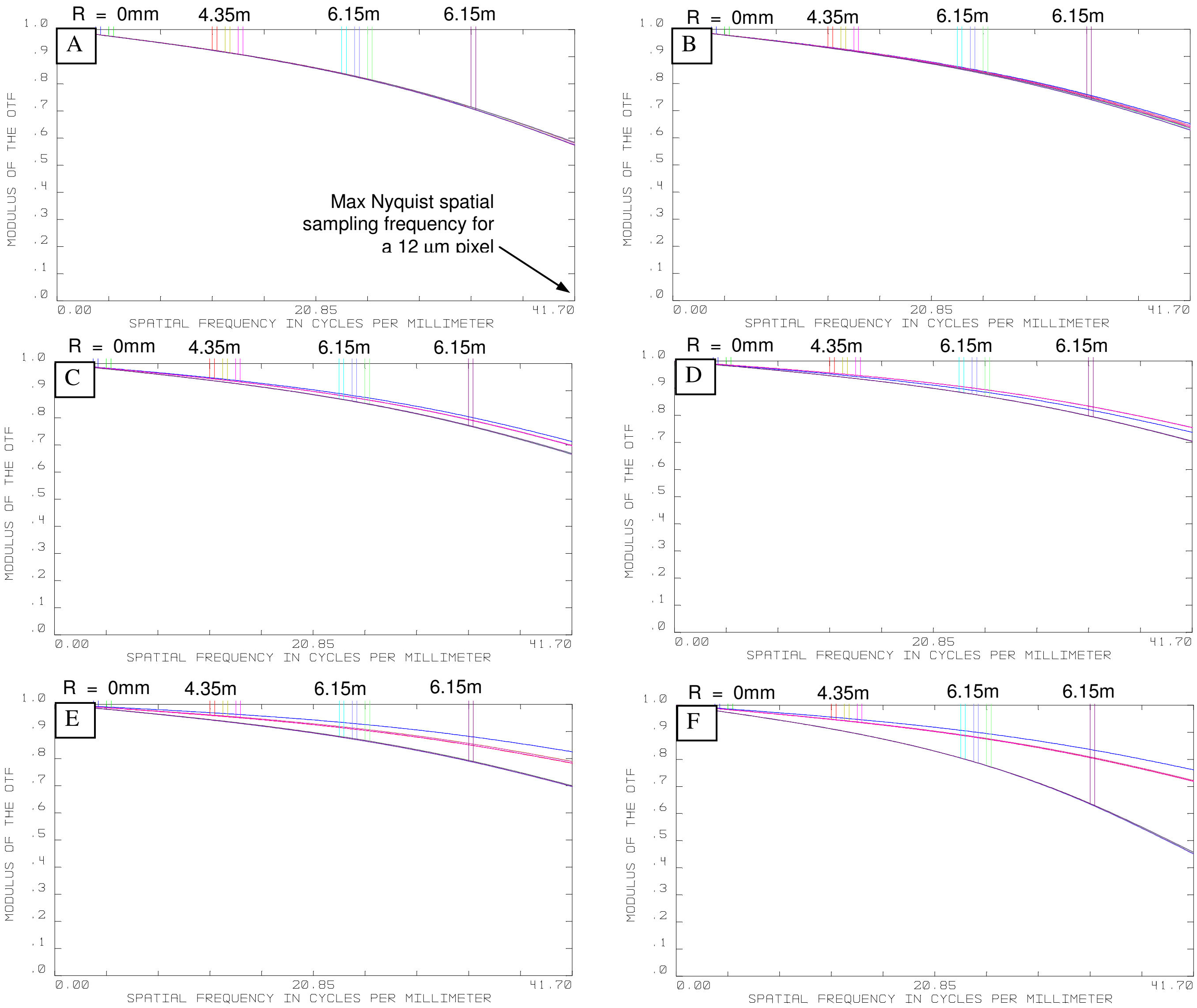

Figure 3 - Huygens Optical Modulation Transfer Function (Wideband Filter) for Various Image Plane Field Points of Radius, R, over CHAMP's Range of Magnification, M. A) M=4.4, B) M=3.0, C) M=2.0, D) M=1.0, E) M=0.3, F) M=0.01.

4. CHAMP FIELD IMAGING

The variable magnification/focus optical design allows CHAMP to image targets with significant surface roughness as well as provide range-finding estimates for precision arm placement relative to small features. Figure 4 summarizes CHAMP's imaging capability for interacting with field targets at handlens/microscopic resolutions.

Microscopic viewing of rough surfaces is performed by sampling a three-dimensional surface over a range of closely spaced working distances and applying z-stack image compression. In such a case, an auto-focus solution for the target is first found by locating the best-focus position for lens cell 2 (Note lens cell 2 translates relative to lens cell 1 in the mechanical implementation of the instrument). While a number of algorithms can be applied to find the best focus region for z-stacking [7] (by essentially measuring the degree of high spatial frequency information in an image), a very simple and sensitive metric that has been initially proposed for a flight version of CHAMP is to use the compressed file size of the z-stack images (see Figure 5). Once a best focus solution has been found, multiple raw images (typically 10's of images ultimately dependent on surface roughness) spaced at the instrument's depth-of-field (~40 micron at microscopic resolutions) are acquired about the best focus position (Figure 4C-G). The in-focus portions of these images are then software-filtered to remove the large volume of "out-of-focus" image data in the z-stack of images. This filtering process effectively compresses the z-stack of images down into a single "in-focus" image (Fig. 4E). To date, a Sobel of the convolution of an image has been used for this z-stack software compression filter, however, continuing work has been proposed for more complex algorithms to address minimizing any slight image

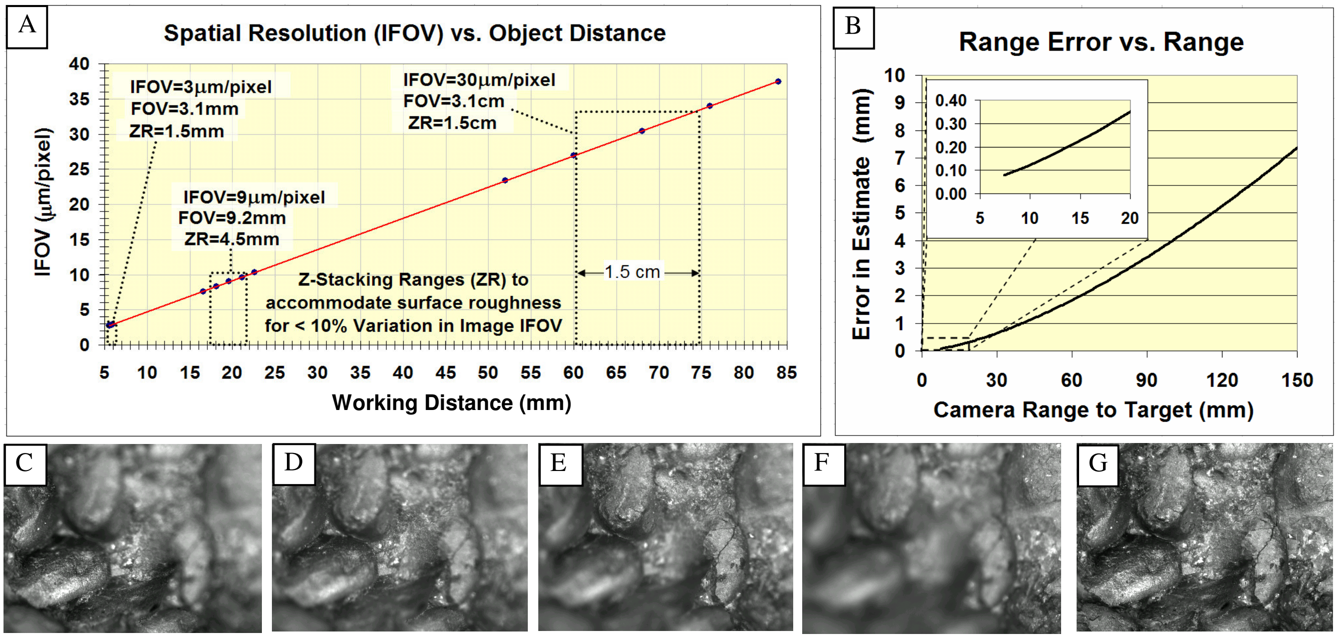

Figure 4 - A) CHAMP's Pixel Resolution (µm/pixel) as a Function of Working Distance. B) Depth-of-field-Limited Precision Range-Finding Estimates with CHAMP. C)-F) Raw Monochromatic MIDP CHAMP Images of Hematite at Slightly Different Working Distances Compressed into E) a Single Composite In-focus "Z-stacked" Image.

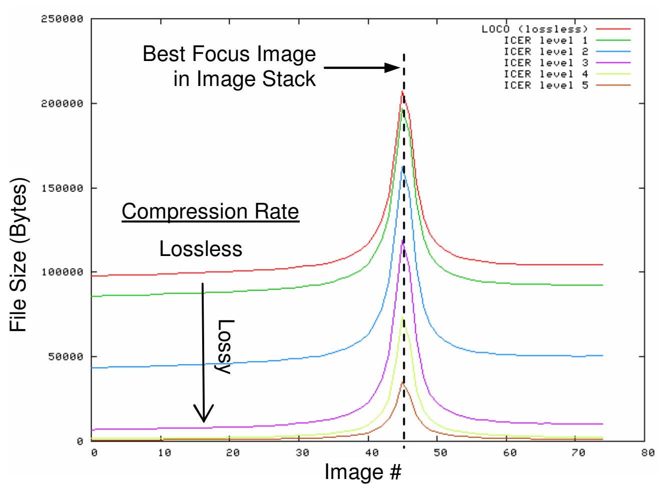

Figure 5 - Example of Best Focus Calculated from Compressed Image File Size.

distortion that may occur due to the subtle change in magnification over the range of the acquired image stack.

Due to the inherently small FOV's associated with microscopy (~mm's as shown in Table 1), accurate arm placements based on CHAMP progressive context image information is highly desirable. For precision arm placement, 3D location of a small target can be determined by coupling the 2D location of a target in CHAMP's object plane with the working-distance of the object plane from the camera. This working-distance can be estimated within the DOF of the lens system by measuring the relative distance (calibrated) between lens cells 1 and 2 for the target's best-focus position (Fig. 4F).

5. Illumination System

The original MIDP CHAMP instrument utilized 20 white LED's for illumination near and at peak magnification. This design has been miniaturized and upgraded (Fig. 6) with fiber optics to support a smaller "snub nose" in order to minimize the amount of material that must be removed when imaging an abraded surface .

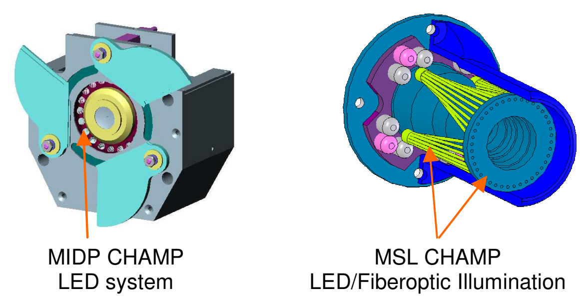

Figure 6 - CHAMP Illumination System Design

The upgraded illumination system consists of four independent quadrants as shown in Figure 6 which serve as a built in redundancy against failure of any individual quadrant. Any of the four quadrants can be illuminated independently creating oblique lighting conditions for viewing surface topography with either white or UV light. This illumination system design includes a reflective surface on the inside of the snub nose to optimize microscopy illumination intensity over a large working distance as shown in Figure 7A. Figure 7B illustrates the exposure time necessary to achieve 50% full well per pixel with a MER

CCD detector after light from the white-LED system illuminates different reflectant surfaces and returns through a set of MER Pancam filters (as a design case) using 120mW$_e$ LED's (6mW light output). In all cases, the detector signal-to-noise (SNR) is greater than 100.

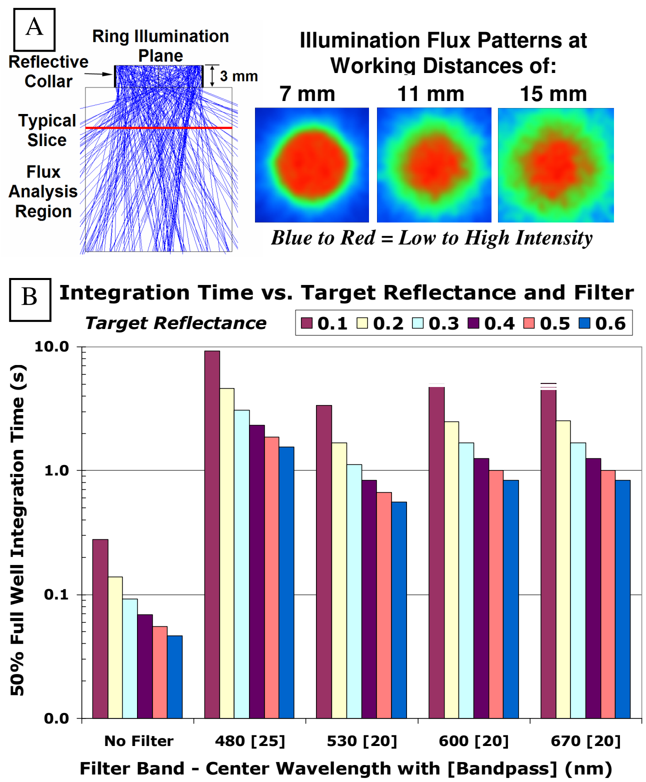

Figure 7 - A) CHAMP Snub Nose Illumination Flux. B) Time to 50% Full Well using Various Pancam Filters and Target Reflectances with 4 White LED, Full Quadrant Illumination

6. MECHANICAL DESIGN

To support qualification of the CHAMP instrument eventually for flight, a number of mechanical design upgrades from the original MIDP have been baselined. Figure 8 illustrates the conceptual mechanical design of a CHAMP flight instrument.

Optomechanical Design – A kinematic translation stage provides the necessary relative motion between lens cell 1 and lens cell 2 (within the required optical tolerances) for CHAMP's variable working-distance/magnification over extreme temperature ranges. As previously noted, the lens cells (optical mounts designed for extreme temperature ranges) are assembled and precision-aligned independently before being integrated into the overall assembly. The entire camera assembly has been designed for easy integration/de-integration with a future host vehicle.

Mechanical Coupling to a Target – At highest resolution microscopy, CHAMP can potentially be susceptible to image blur due to external disturbances (e.g. wind in terrestrial environments) applied over the exposure times shown in Fig. 7B. To alleviate this potential problem, three spring-loaded pins were incorporated into the MIDP design to provide a preload against a target which removes backlash in robotic arm gears and joints that act as soft springs susceptible to the external disturbances. Although much less of an issue for Mars and vacuum environments, the proposed flight version of the instrument incorporates the same design concept with the following modifications:

1) Springs with a longer stroke to provide a nearly constant spring force during the preload. Dry lubricants are used for the spring-loaded pins to increase life.

2) Short spiked ends with dust wipes to minimize collected debris and debris in the spring mechanism. The spring mechanism is sealed from the internal optical components of the instrument.

Dust Mitigation – Given the likely and common interaction of CHAMP with the Mars saltation zone (zone of tumbling windblown particles near the Mars surface [12]) as well as the likelihood that CHAMP may be in the vicinity of particles generated from abrasion and coring processes (i.e. on a common robotic arm), CHAMP incorporates a dust cover mechanism to protect the imager when not in use. This mechanism uses the same mechanical design philosophy and motor as were used on the MER MI to provide a seal against the outside environment without sliding motion at the seal interface.

Planetary Protection – The flight version of the CHAMP instrument is sealed such that the instrument (minus the dust cover mechanism which is separately sterilized and subsequently assembled) can be immersed in an alcohol bath up to a filtered vent in order to meet planetary protection requirements.. In general, this instrument has been designed to withstand dry heat sterilization requirements.

7. CONCLUSIONS AND FUTURE WORK

We have described the recent development and demonstration of the CHAMP field camera/microscope which can image over an extreme range of spatial scales. At peak magnification CHAMP has the highest spatial resolution currently known for a spaceflight imager in the visible band. Furthermore, a flight version of the instrument has been conceptually designed with preliminary analysis that supports the future development of the instrument for spaceflight conditions. This work appears very promising for enabling future robotic spacecraft missions to utilize a single all-purpose camera for multi-functional imaging across all spatial scales relevant for a mission (Fig. 9).

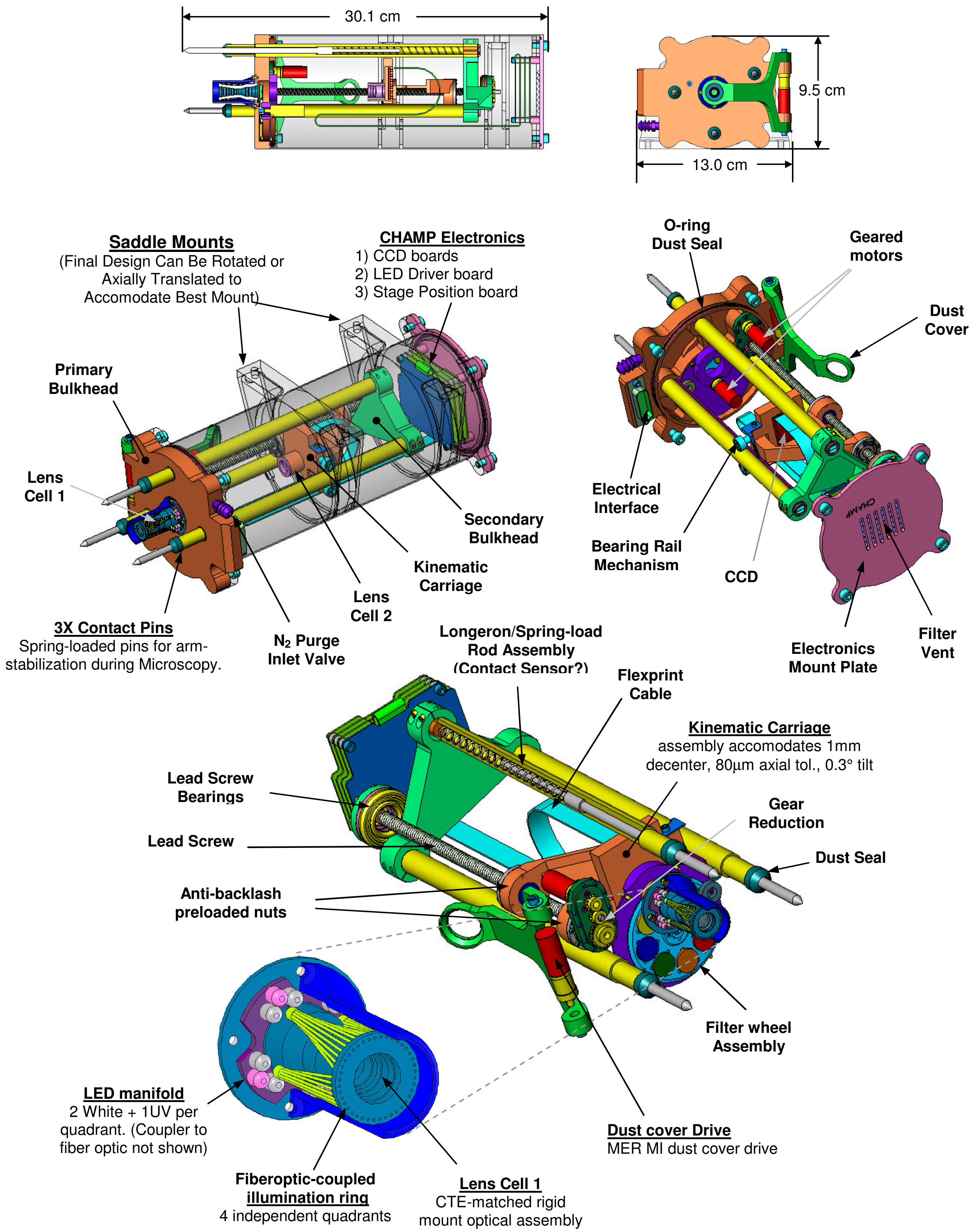

Figure 8 – Concept Flight CHAMP Mechanical Design

The MIDP version of this instrument is currently integrated with the NASA Ames K9 rover (Fig. 1). Future work would couple the ongoing single command arm placement robotics software work with CHAMP imaging over a range of spatial scales. This software development, in particular, would include focal plane merging (specific to CHAMP) from two viewpoints to allow the "cyclops" CHAMP camera to produce variable baseline stereo-images across its magnification range (Figure 10 illustrates a stereo-image example for a single microscopic imager). Such a development would demonstrate the necessary capabilities for future rover reconnaissance and robotic arm investigations using a single CHAMP camera.

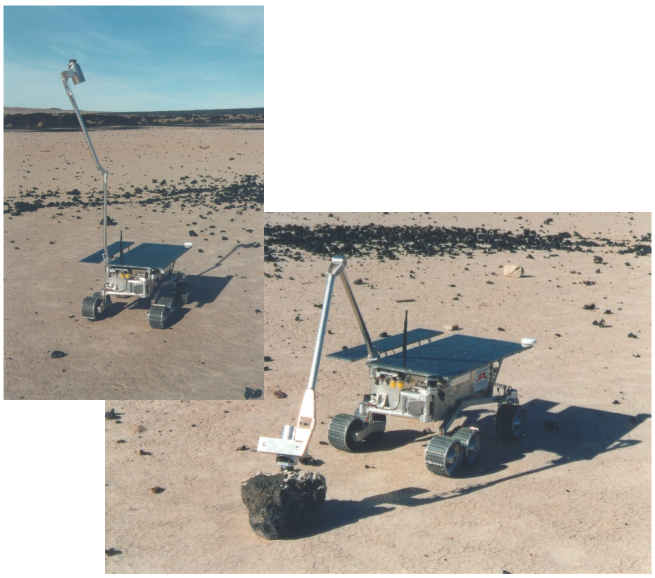

Figure 9 – Future CHAMP Integration on a Deployable Arm/Mast Would Allow Mast and High Resolution Contact Instrument Imaging to be Integrated into a Single Instrument on a Single Robotic Appendage [14].

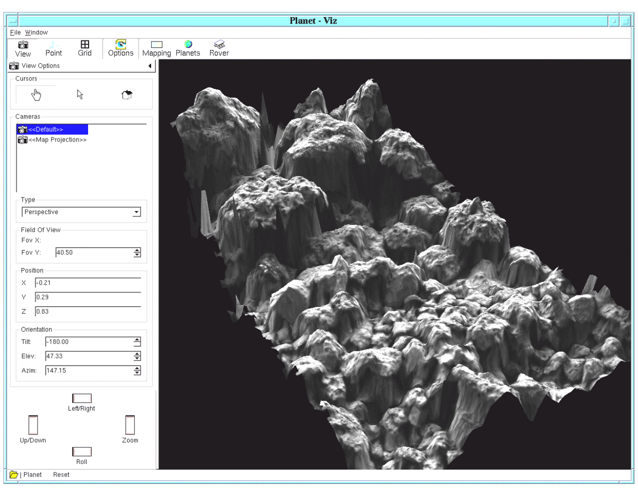

Figure 10 – Example of a Stereo-Image Produced from Focal Plane Merging Single Camera Images Acquired at Two Different Perspectives

Finally, future work specific to the camera design would augment the illumination system with high power pulsed diodes to reduce the overall exposure times shown in Fig. 7

ACKNOWLEDGEMENTS

The research described in this paper was preformed at the Jet Propulsion Laboratory at the California Institute of Technology and the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado under a contract from the National Aeronautics and Space Administration. It was principally funded under the Mars Instrument Development Program (MIDP) as well as internal JPL Bid and Proposal funding. We would also like to extend a special thanks to a number of individuals without whom CHAMP would not exist: George Lawrence, Ritch Shidemantle, Tim Crist, Gabe Hamilton, Jack Loui, Michael Buck, Abhi Tripathi, Sean Sherrard, Sasha Pearlman at Opto-Alignment Technology.

REFERENCES

[1] S.W. Squyres, et al. "The Opportunity Rover's Athena science investigation at Meridiani Planum, Mars". Science, Vol. 306 (5702): 1698 (2004)

[2] S.W. Squyres, et al. "In situ evidence for an ancient aqueous environment at Meridiani Planum, Mars". Science, Vol. 306 (5702): 1709 (2004)

[3] K.E. Herkenhoff, et al. "Evidence from Opportunity's microscopic imager for water on Meridiani Planum". Science, Vol. 306 (5702): 1727 (2004)

[4] S.W. Squyres, et al. "The Spirit Rover's Athena Science Investigation at Gusev Crater, Mars". Science, Vol. 305 (5685): 794 (2004)

[5] K.E. Herkenhoff, et al. "Textures of the soils and rocks at Gusev crater from Spirit's Microscopic Imager". Science, Vol. 305 (5685): 824 (2004)

[6] Personal Conversation with MER Scientist, Dr. Hap McSween.

[7] J. F. Bell et. al. "Mars Exploration Rover Athena Panoramic Camera (Pancam) investigation", J. Geophys. Res., Vol. 108(E12), 8063, doi:10.1029/2003JE002070, 2003.

[8] K. E. Herkenhoff et.al. "Athena Microscopic Imager Investigation". J. Geophys. Res., Vol. 108(E12), 8063, doi:10.1029/2003JE002070, 2003.

[9] P. Smith, H. U. Keller, 2001, "The Robotic Arm Camera for Mars Surveyor 2001", Workshop on Mars 2001.

[10] R.O. Reynolds et. al. "Design of an Active Focus System for a Mars-bound Robotic Arm Camera", Optomechanical Design and Precision Instruments, SPIE Vol. 3132, 1997. pg. 78-85.

[11] N. Thomas, et. al. 2003, "The Microscope for the Beagle 2 Lander on ESA's Mars Express", 6th Interntl. Conf. Mars 2003.

[12] J. Boynton et. al. 2002, "Camera Handlens Microscope (CHAMP)", MIDP Final Report, JPL Contract #961-495.

[13] R. Greeley. "Introduction, Sand and Dust on Mars", *Sand and Dust on Mars*, NASA CP-10074, Feb. 1991.

[14] http://robotics.jpl.nasa.gov/tasks/scirover/science /instruments/homepage.html

BIOGRAPHY

John Boynton *is currently at the Jet Propulsion Lab where he is the Flight System V&V Systems Engineer and Requirements Systems Engineer for the 2007 Phoenix Mars Scout lander. He was the CHAMP Project Manager and optical designer during the MIDP development phase (1998-2002) completed at LASP (Laboratory for Atmospheric and Space Physics, University of Colorado). Recently, he has been involved in the following projects: Deputy Team Lead on the Mars Astrobiology Field Lab (JPL, 2003), and CoI /Payload Manager for HOMER Mars Scout mission proposal (2002, while at Firestar Engineering of which he was a cofounder). Other projects while at LASP included: Study Manager for Mars Sample Return Technical Approach Study (2001), MARCI camera calibration team member (Surveyor 98 Mars Climate Orbiter), DENEM payload proposal for 2003 Mars lander (1999), and CODI (Cloud Ozone Dust Imager) Mars wide angle camera prototype for NASAs PIDDP (1998-1999). Boynton was awarded the M.S. in Aerospace Engineering (Fall 1999) by University of Colorado (Boulder), was previously enrolled in the Ph.D. Program in Molecular Biology at Temple University (1993-1995), and received a Bachelor's degree in Interdisciplinary Natural Sciences from University of South Florida (1993).*

Greg Mungas *currently works at the Jet Propulsion Laboratory as an advanced studies lead for the Mars Program Office. He also is currently an institutional principal investigator on three inter-related instrument development technologies in NASA's Planetary Instrument Definition and Development Program (PIDDP) and Astrobiology Instrument Development Programs (ASTID), as well as a Principal Investigator on two Mars Technology research development programs in Propulsion and Rover technology. Recently he was the proposal manager, CoI, and technical led for the proposed MSL CHAMP flight instrument. Prior to joining JPL, he was a co-founder of Firestar Engineering, LLC where he initiated and lead multiple research studies including serving as a multi-institutional proposal manager for the HOMER Mars Scout mission proposal (2002) with the SETI Institute, the Boeing Company, and partners. At the Laboratory of Atmospheric and Space Physics (LASP), he developed and prototyped a system for detumbling and sun-pointing hitchhiker spacecraft as well as performing a number of ADCS, propulsion, and dynamics simulation tasks and leading a UnESS spacecraft technical proposal team. He received a BS in mechanical engineering from the University of Alaska Fairbanks (1998) with Honors, and an MS degree in Aerospace Engineering from the University of Colorado (2000).*

Cesar Sepulveda *has been at the Jet Propulsion Laboratory since 1981, with a two year detour at the Hughes (now Raytheon) Santa Barbara Research Center. He is currently a senior member of the JPL technical staff in the design of optical systems for remote sensing instruments in the Observational Systems Division. He is the designer of the Mars Pathfinder Sojourner Rover cameras, as well as other systems for use in future planetary missions. He received the BS degree in Physics from the National Autonomous University of Mexico in 1970 and the MS degree in Optical Sciences from the University of Arizona in 1976.*

Mark A. Balzer *is currently a Senior Staff Engineer at the Jet Propulsion Laboratory in Pasadena, CA, where he designs mechanisms for spacecraft and space instruments. He received a Bachelor of Engineering with High Honor in mechanical engineering in 1987 from Stevens Institute of Technology, an MS in mechanical engineering in 1991 from SUNY at Buffalo, and a PhD in mechanical engineering in 1998 from the University of Illinois at Urbana-Champaign.*

Ted Fisher *is a founding member of Firestar Engineering, and is Lead Software Research Development Engineer on the following NASA funded projects: Multi Spectral Imager (MSI) 2003 PIDDP, LIBS/Raman in a Fiber 2004 ASTID, and Nitrous oxide Oxidizer/Fuel Blend Optimized Breakdown System (NOFBOBS) 2004 Mars Technology Award. Prior to Firestar Engineering, he took over the original software lead at LASP for the MIDP CHAMP (2002) developing image reconstruction software and performing the final electrical and software integration of CHAMP with the K9 rover. At LASP he also developed software and data analysis tools for the Student Nitrous Oxide Explore (SNOE) satellite and Mars Sample Return Technical Trade studies conducted in collaboration with Ball Aerospace and JPL. He is currently completing his BS* *in Computer Science at the University of Colorado, Boulder in (June 2004).*

Matt Deans *currently works in the Intelligent Robotics Group at NASA Ames Research Center. His research is focused on vision-based navigation and contact instrument placement with NASA Ames' K9 rover. Recently he was a lead software developer for the Micro-Imager software toolkit used on the MER mission. He received his BS in Robotics from Lehigh University and a PhD in Robotics from Carnegie Mellon University.*

Luther Beegle *is a Research Scientist at the Jet Propulsion Laboratory where he has been employed since 2001 after spending 4 years at JPL and the California Institute of Technology as a Post Doctoral Researcher. He is an experimental physicist by training and has extensive astrobiological science interests as well as experience developing instrumentation for space applications. These developments include projects as both a Principal Investigator and a Co-Investigator and include the designing and testing of ion mobility spectrometers, charged particle optics, organic molecule extraction techniques, microwave discharge plasma sources, and cylindrical ion trap mass spectrometers funded under the Planetary Instrument Definition and Development Program (PIDDP), Astrobiology Instrument Development Program (ASTID) and Mars Instrument Development Program (MIDP). He received his BS in Physics from the University of Delaware in 1990, and his MS and PhD in Physics from the University of Alabama At Birmingham in 1995 and 1997 respectively.*

Daniel Klein *currently works as a contractor for Coherent Technologies of Louisville, CO. While working at LASP, he was lead electrical engineer for CHAMP. Mr. Klein has also studied aerospace and biomedical engineering and applied this knowledge to a variety of projects including the design of the data system used in the space shuttle's research double module. Prior to Mr. Klein's engineering career, he served in the U.S. Army as a special operations flight medic. He received a BS in electrical engineering from the University of Colorado, Boulder.*

Pascal Lee *is co-founder and chairman of the Mars Institute, a planetary scientist at the SETI Institute in Mountain View, CA, and the Principal Investigator of the NASA Haughton-Mars Project (HMP) at NASA Ames Research Center in Moffett Field, CA. He holds an Ingénieur degree (ME) in Engineering Geology & Geophysics from the University of Paris (1987), and a MS (1993) and Ph.D. (1997) in Astronomy & Space Sciences from Cornell University.*

Harold Sobel *has been at the Jet Propulsion Laboratory since 1988. He is currently a senior engineer working in the area of instrument systems analysis. He has been the systems analyst on numerous activities including AVIRIS (Airborne Visible/Infrared Imaging Spectrometer), TES (Tropospheric Emission Sounder, on EOS-Aura), and VIMS (Visible and Infrared Mapping Spectrometer, on Cassini). He received his B.A. in chemistry in 1964 from Franklin and Marshall College and his Ph.D. in physical chemistry from Northwestern University in 1969.*